Digital Array Radar: A New Vision

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Introduction: Naval operations are moving closer to shorelines in many regions of the world. Included in this environment are commercial and military communications, increasingly complex electromagnetic interference (EMI), and the need to detect both small moving targets embedded in severe clutter as well as other challenging targets (e.g., tactical ballistic missiles). This operational environment strains the performance of a number of current radar sensors onboard ships.

Shipboard array radars of today are largely analog-based. Despite the enhancements being made, they still are falling short of the potential performance improvements that could be embodied by fully digital adaptive arrays. New technologies are needed to support the development of higher performing shipboard radars. The success of the information technology (IT) market and other commercial technologies are leading the development of new digital components that could be incorporated in the design of high-performance digital array radar. The wireless market, in particular, has made great strides in improving the performance of digital cell phones and other technologies through smaller packaging, weight reduction, improved analog-to-digital (ADC) and digital-to-analog converters (DAC), and increased dynamic range of RF/microwave components. In addition, for rapidly configuring simple logic functions in an integrated chip and at a low cost, field-programmable gate arrays (FPGAs) have become an attractive alternative to application-specific integrated circuits (ASICs).

Future Shipboard Radar Challenges: Strong land clutter, man-made sources of EMI (e.g., cell phone towers, other radars), and jamming signals coming from different directions are just a few of the factors that fleet radars must contend with.

Extended land clutter that competes with small targets is a difficult problem. Many current shipboard radars have insufficient dynamic range (i.e., linearity) to pass the high-peak clutter levels without saturating the entire receiver. By digitizing analog radar data (i.e., through the use of an ADC) at the element level, the dynamic range can be enhanced.

Multiple jamming signals arriving from different directions pose a separate problem. As a ship navigates along coastal regions and scans the volume for targets, jammer energy can enter at any angle and strongly affect the ability of the array radar to form antenna beams for different targets. Analog beam formers are limited in terms of their performance since a single ADC is typically used at a summing point. The ideal solution to the jamming and clutter problem is to place an ADC at every radiating element in an array radar system and sum the contributions to form beams and nulls digitally with a digital beam former (DBF). Several benefits are derived from this solution: increased flexibility of forming array beams, improved time-energy management, enhanced dynamic range, and a potentially lower cost of implementation over time.

Supporting Technologies and Technological Hurdles: The ADC is critical to the performance of the digital beam former. The number of bits achievable by the ADC and the number of receive channels in the beam former impacts the dynamic range that can be obtained. Although their performance is steadily improving, the sampling rates of commercial ADC technologies are still not sufficient to support digital array radars. DACs have similar performance issues.

Development of Digital Array Radar: Early concepts of digital-array radar (DAR) began in the 1980s. As ADC, DAC, and wireless technologies began to improve in the mid 1990s, the DAR implementation was starting to become more realistic. In FY00, the Office of Naval Research (ONR) funded a new program to design, develop, and demonstrate a DAR test bed for a potential prototype for the Navy.[1] Three organizations were involved in this initial effort: NRL, Massachusetts Institute of Technology (MIT) Lincoln Laboratory, and the Naval Surface Warfare Center (NSWC) in Dahlgren, Virginia. Figure 1 is a simple block of one DAR concept that was considered in FY00. As shown, digital processing encompasses the beam former and waveform generator entirely. Digital transmit waveforms and control are generated, converted to optical, and distributed

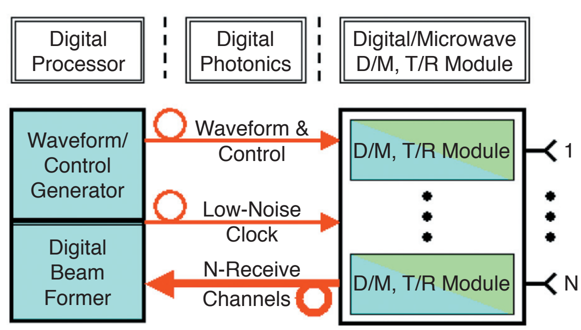

FIGURE 1
Basic architecture of a digital array radar.

optically to an array of digital/microwave transmit/receive (T/R) modules behind the array antenna of *N*-radiating elements. Figure 2 shows a rectangular array antenna for the DAR test bed. FPGAs were considered in the implementation of a DBF; Fig. 3 shows an example DBF implementation.

FIGURE 2
L-band phased array antenna with circular radiating elements (MIT Lincoln Laboratory development).

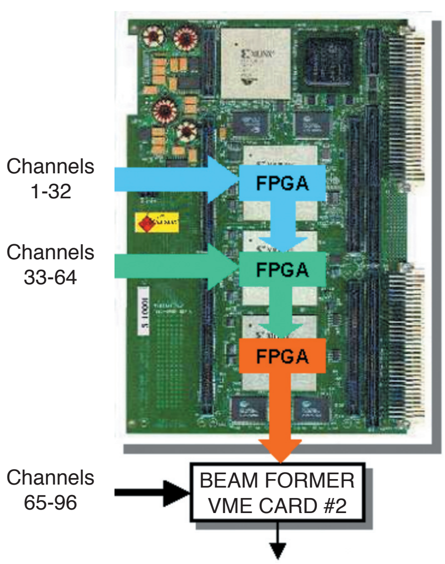

FIGURE 3
VME card for a 96-channel digital beam former.

Summary: The U.S. Navy is operating closer to shore where large land clutter, multiple jammers, EMI, and small targets are stressing the limit of current array radar systems. This operational environment requires unprecedented performance improvements that could be achieved with digital components and concepts. The success of the IT market and emerging commercial digital technologies are driving the state of the art of components for phased array radar systems toward a fully digital array system. Previous developments have included a small DAR test bed that was designed with mostly digital hardware. Currently, a study is being conducted to lay the foundation for a DAR-type of system.

[Sponsored by ONR and PMS-426]

Reference

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Traps in GaN-based Microwave Devices

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Introduction: The Navy's requirement for a new generation of high-power, high-frequency, solid-state amplifiers for long-range detection cannot be met by current Si and GaAs device technologies because of limitations in the basic materials properties. A promising material system is the nitrogen-based wide-bandgap semiconductors (AlN, GaN, InN, and their alloys). In addition to excellent thermal and electron transport properties, these materials support the growth of a high-quality hetero-interface, such as AlGaN/GaN. Such heterostructures are necessary for the formation of a two-dimensional electron gas (2DEG)—a thin, high-mobility channel confining carriers to the AlGaN/GaN interface region. While excellent device characteristics have been reported for these high electron mobility transistors (HEMTs), they have not been incorporated into Navy systems because these characteristics are not always reproducible—a result of deep traps in the nitride material. A deep trap may be regarded as an impurity or crystal defect that captures a mobile charge carrier and keeps it strongly localized in the neighborhood of the trapping center. Deep traps can produce *current collapse,* a distortion of the device current-voltage (I-V) characteristic that is of particular concern because it ultimately limits the output power of the device. To eliminate the trapping centers that cause this phenomenon, the responsible defects must be detected, characterized, and identified. In this article, we describe a unique optical technique that has been developed through a collaboration of materials growth, device fabrication, and device characterization that now provides this capability.

Current Collapse: When a large bias voltage is applied between the source and drain of a field effect transistor (FET) (such as the HEMT structure depicted in Fig. 4), the electrons in the conducting channel are rapidly accelerated. These "hot carriers" gain enough kinetic energy from the large electric field to be injected into an adjacent region of the device structure. If this region contains a significant concentration of traps, the injected carriers can become trapped. The resulting reduction in drain current, referred to as "current collapse," can severely compromise the performance of a microwave FET. In the case of the HEMT in Fig. 4, the hot carriers are trapped in the high-resistivity GaN buffer layer, which is known to contain a high trap concentration. The collapsed drain current can be restored by light illumination, which frees (photoionizes) the carriers from the traps. Since the trapped carriers represent a negative charge distribution in the GaN, the resulting transverse electric field causes the photoionized carriers to rapidly drift back to the conducting channel, thus restoring the drain current. This light-induced increase in the collapsed drain current is the basis for the photoionization spectroscopy technique that enables the detection and characterization of the responsible traps.[1]

Photoionization Spectroscopy: Measurement of the wavelength dependence of this light-induced drain current increase, normalized by the amount of incident light, has been shown to reproduce the photoionization spectrum of the trap.[2] This reflects the absorption spectrum associated with the ionization of the carrier from the trap and is a unique characteristic of a given trap. Consequently, this spectrum can be used as a signature of the trap. Figure 5 shows such spectra for an AlGaN/GaN HEMT structure and a GaN metal semiconductor FET (MESFET) that uses a thick n-type (electrons from impurities carry the current) GaN conducting channel in place of the 2DEG of the HEMT. In addition to the expected absorption at the GaN bandgap, two broad absorption bands are observed below the gap, associated with two distinct traps (labeled Trap1 and Trap2). The deduced absorption threshold energies reveal that Trap1 is roughly situated at midgap, while Trap2 is very deep (roughly 0.5 eV above the valence band). Similar absorptions observed in both types of devices indicate that the same traps (in the GaN buffer layer) are responsible for current collapse in both devices. The lack of any response at the bandgap of the AlGaN confirms the location of these traps in the GaN.

Modifying these measurements to investigate, at a fixed wavelength, the variation of the drain current increase with the amount of incident light has shown that the areal concentration of each trap can be determined.[2] The technique was applied to devices fabricated on a set of four wafers, each prepared with a different trap concentration by growing the GaN buffer layer at a different growth pressure. Figure 6 shows the variations in the resulting trap concentrations with growth pressure.[3] The concentration of Trap2 was found proportional to the concentration of carbon in the layers, as determined from secondary ion mass spectrometry (SIMS) measurements shown in the figure. This identifies Trap2 as a carbon-related defect.

Conclusions: Photoionization spectroscopy is a powerful tool for investigating traps that cause current collapse in electronic device structures. The technique provides a unique signature for each trap, as

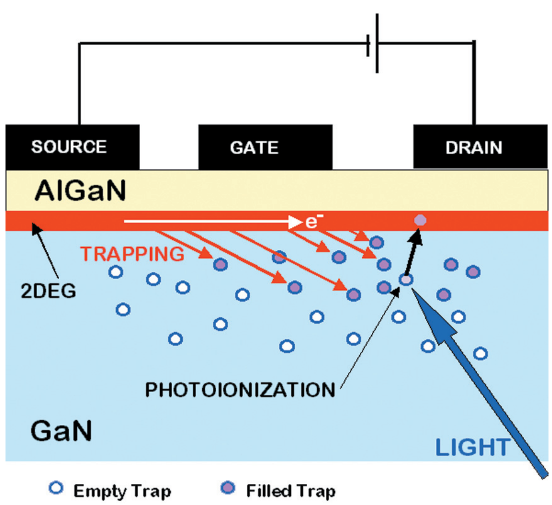


FIGURE 4
Current collapse in an AlGaN/GaN HEMT structure due to trapping of hot carriers injected into the high resistivity GaN as the result of a high drain-source bias. The collapsed drain current is restored by light illumination through photoionization of the trapped carrier.

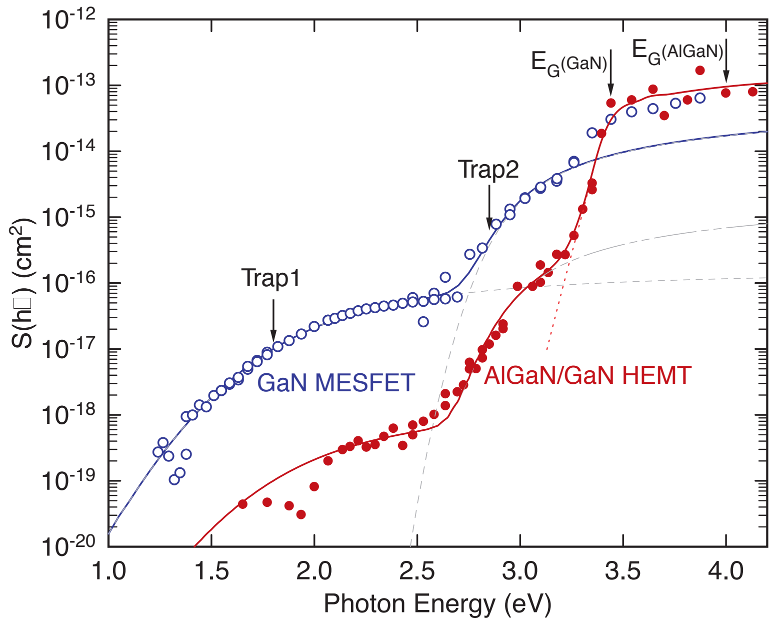
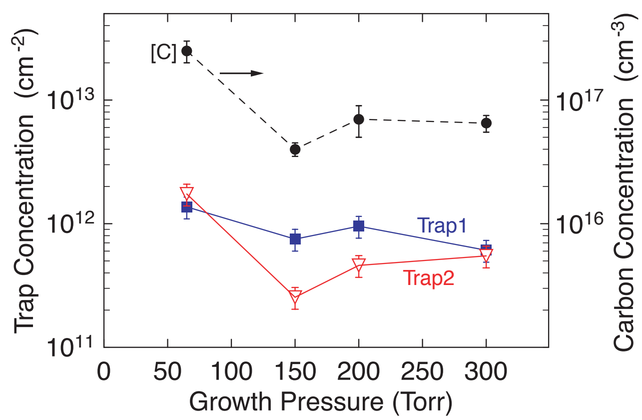


FIGURE 5
Spectral dependence of the normalized drain current increase S(hν), induced by light illumination of an AlGaN/GaN HEMT and a GaN MESFET.

FIGURE 6
Dependence of the concentration of traps responsible for current collapse in AlGaN/GaN HEMT structures on the reactor pressure used during organometallic vapor phase epitaxial growth of the high-resistivity GaN layer. The variation of the Trap2 concentration tracks that of carbon impurities in the layer (as measured by SIMS), indicating that a carbon-related defect introduced during growth is responsible for Trap2. (From Ref. 3.)



well as detailed trap characteristics. The technique is currently being expanded to investigate other trap-related phenomena occurring in nitride-based microwave devices.

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Polar Reformatting for ISAR Imaging

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Introduction: The Navy's increased interest in operations in littoral environments requires reliable identification of a vast number of small targets. Inverse synthetic aperture radar (ISAR) is a radar imaging technique that uses target motion to achieve the Doppler discrimination that is needed to form a 2-D image. The key to using radar imaging for small-target identification is the production of high-resolution, well-focused imagery. Acceptable imagery can be produced using traditional range-Doppler processing through the utilization of modern motion-compensation techniques. While motion compensation can provide good focus for a limited number of scatterers on the target, a different approach to ISAR imaging is required to achieve a fully focused ISAR image. The problems that need to be addressed deal with target rotation that is not linear and with scatterers that migrate through range cells during the image formation period. These problems are amplified because of the need for fine range and Doppler resolution in the imagery. Polar reformatting is a technique that has been developed to address these problems in spotlight synthetic aperture radar (SAR) imaging and has been adapted by NRL for use in ISAR imaging.

Background: Polar reformatting is an image formation technique based on tomographic reconstruction techniques originally developed for medical imaging.[1] Tomographic image formation involves reconstructing the spatial representation of an object using the Fourier transform of a set of observations, each being a projection of the object onto a line, taken over a series of aspect angles. This series of observations populates a region of Fourier space and can be used to reconstruct an image of the object using inverse Fourier transform methods. A received radar pulse is the projection of the electromagnetic scattering from the target onto the radar line of sight and can be used for this technique. The difference between tomographic reconstruction using radar signals and traditional tomographic reconstruction is that the radar's signal is modulated by the carrier frequency of the radar. As a result, the Fourier transform of the radar's pulse produces a line segment in 3-D Fourier space that is offset from the origin by the carrier frequency at an angle determined by the angle of the radar line of sight. As successive pulses are received and the aspect between the radar and the target changes, the line segment sweeps out a data surface in 3-D Fourier space (Fig. 7). Once the data surface is formed, an image is reconstructed by transforming the surface into the spatial domain using a variety of techniques developed for SAR.[2]

ISAR Imaging Using Polar Reformatting: Processing for ISAR image formation is similar to processing for spotlight SAR imaging. In ISAR processing, the main difference is that the motion of the target provides the change in aspect necessary for Doppler processing; in spotlight SAR, the change in aspect comes from the motion of the radar. As a result of this difference, the aspect change, over time, between the radar and the target is both unknown and uncontrollable in the ISAR imaging case. Because the aspect change defines the shape of the data surface, the rotation of the target must be determined before polar reformatting can process the data into imagery. Initial efforts concentrated on developing a model for and estimating the parameters of the target rotational motion and using these estimates to form the data surface. Because this approach did not yield a closed-form solution to the target motion parameters, we decided to try an approach in which we modeled the data surface directly and used measurable motion quantities to estimate the data surface model parameters. We chose a quadratic data surface model because it was as simple as possible (fewest model parameters) but still allowed us to compensate for most of the nonlinear rotational motion in the target. Also within the surface, the spacing between the data line segments was also modeled as a quadratic function. Using this model, we have two parameters of interest: the quadratic term representing the curvature of the data surface (called the out-of-plane acceleration) and the quadratic term representing the line segment spacing (called the in-plane acceleration).

Polar Reformatting System: The implementation of this technique involves taking motion measurements from the data, estimating the data surface model parameters, projecting the data surface onto

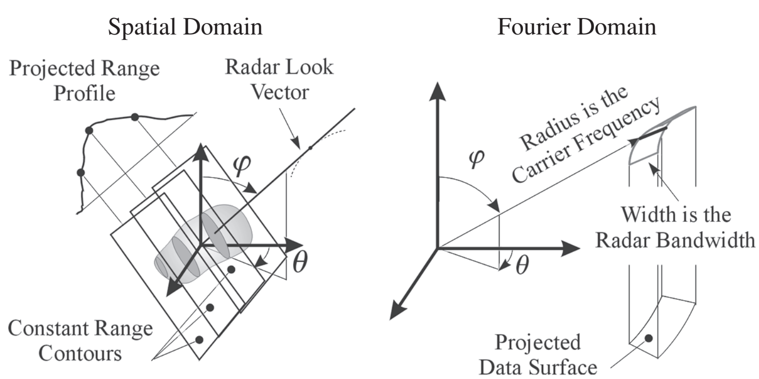

FIGURE 7
Representation of the received radar pulses for a rotating target in the spatial and Fourier domains.

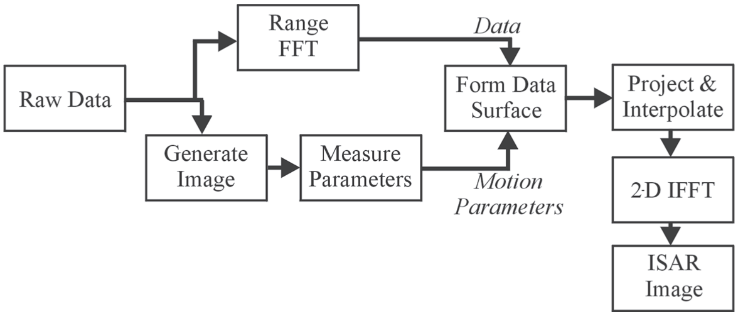

FIGURE 8
Block diagram of the procedure for performing polar reformatting for ISAR.

FIGURE 9
Example ISAR imagery showing the improvement in image quality using polar reformatting.

a planar surface, re-interpolating the data into equally spaced samples, and performing the inverse Fourier transform (IFFT). Figure 8 shows this process. The motion measurements are taken from three locations on a preformed image, where one location is used as a reference point and the other two are used to estimate the surface parameters. Each location provides us with a range, velocity (Doppler), and translational acceleration and a set of simultaneous equations relating these values to the quadratic terms in the model that are used for estimating the model parameters. The projection and re-interpolation steps are done simultaneously for each point on a rectangular grid by back-projecting the grid onto the data surface and performing the interpolation on the data surface. A 2-D Fourier transform of the interpolated data produces the final image. Figure 9 compares imagery produced by using range-Doppler and polar reformatting methods. The improvement in the image quality is clearly shown.

Summary: Polar reformatting is a technique that has been in use for SAR processing for many years and has been shown to produce high-quality imagery. We have successfully adapted this technique to ISAR image formation in which the rotational motion of the target is not known beforehand. This provides NRL with an imaging technique that can produce high-quality imagery in conditions with significantly complex target motion. Past work on polar reformatted ISAR has been for imaging small craft targets, but this technique is currently being applied to imaging ground targets.

[Sponsored by ONR]

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